

# Can a 3+2 Oscillation Model Explain the NuTeV Electroweak Results?

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The  $\sin^2 \theta_W$  result from NuTeV falls three standard deviations from the value determined by global electroweak fits. It has been suggested that one possible explanation for this result could be the oscillation of electron neutrinos in the NuTeV beam to sterile neutrinos. This article examines several cases of masses and mixings for 3+2 neutrino oscillation models which fit the current oscillation data at 99% CL. We conclude that electron to sterile neutrino oscillations can account for only up to a third of a standard deviation between the NuTeV determination of  $\sin^2 \theta_W$  and the standard model.

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NuTeV precisely determines the electroweak mixing angle through the measurement of deep inelastic muon neutrino and antineutrino interactions. Although the final value of  $\sin^2 \theta_W$  obtained by this experiment agrees with previous neutrino-based measurements, the result is anomalously high when compared to the value from global electroweak fits to other data. The NuTeV result,  $0.2277 \pm 0.0013(\text{stat}) \pm 0.0009(\text{sys})$  [1], is roughly three standard deviations above the standard model value of  $0.2227 \pm 0.0004$  [2].

Giunti *et al.* [4] have considered neutrino oscillations as a possible explanation for the NuTeV results, suggesting that if electron neutrinos in the NuTeV beam were oscillating into sterile neutrinos, this could effectively lead to the NuTeV observation. Their paper demonstrated that a 3+1 (three active and one sterile) neutrino model would require very large mixings to the sterile neutrino. Such large mixings are now known to be inconsistent with present oscillation limits. In addition, the proposed oscillations are too large to be consistent with the direct measurement of the electron neutrino content in the NuTeV beam [5]. In this paper, we extend the idea in [4] to oscillation models with two sterile neutrinos, *i.e.* 3+2 (three active and two sterile) neutrino models. For a review of these models and their motivation, see Reference [6].

## I. THE NUTEV DETECTOR AND ANALYSIS

The design of the NuTeV experiment is described in detail in Reference [7]. This experiment used a high energy 800 GeV proton beam, taking data in neutrino and antineutrino modes separately. The NuTeV detector was located 1450 m downstream from the proton target, and consisted of a steel-scintillator target followed by a toroid spectrometer. Two types of interactions can occur:

charged current events (CC), which proceed by  $W^\pm$  exchange, and neutral current (NC), which proceed by  $Z^0$  exchange. Both interactions produce a hadron shower of particles in the calorimeter. For NC events, the shower is accompanied by an undetectable final state neutrino. For CC events, there is instead a muon which can be tracked through the calorimeter and the toroid spectrometer. To lowest order in both QCD and electroweak theory, the ratio of NC to CC rates in neutrino and antineutrino scattering relates directly to  $\sin^2 \theta_W$  [8]:

$$R^\nu = \frac{1}{2} - \sin^2 \theta_W + \frac{5}{9}(1+r)\sin^4 \theta_W \quad (1)$$

$$R^{\bar{\nu}} = \frac{1}{2} - \sin^2 \theta_W + \frac{5}{9}\left(1 + \frac{1}{r}\right)\sin^4 \theta_W, \quad (2)$$

where  $R^{\nu,\bar{\nu}}$  is the ratio of NC to CC total cross sections and  $r$  is the ratio of muon neutrino to antineutrino CC total cross sections.

To extract a value of  $\sin^2 \theta_W$  from the data, NuTeV does not measure total cross section ratios, but rather measures experimental ratios of NC to CC candidate events. NuTeV differentiates NC and CC interactions simply by the measured length of the event [1]. NC interactions strictly produce hadronic showers and appear as short events in the detector. Longer events are likely to be extended by virtue of containing a muon, and thus are identified as CC events. The total number of short and long events ( $N_{exp}^S$  and  $N_{exp}^L$ , respectively) are measured and from them, the experimental ratio,  $R_{exp} \equiv N_{exp}^S/N_{exp}^L$  is determined in both the neutrino and antineutrino data. These ratios include the effects of experimental cuts, cross-talk between candidates in the numerator and denominator, final state effects, and non-muon neutrino backgrounds.

The second largest background to  $N_{exp}^S$ , accounting for  $\sim 5\%$  of short events in neutrino mode and  $\sim 6\%$  in antineutrino mode, results from electron neutrino contamination in the beam, the dominant source of which are  $K_{e3}^\pm$  decays. The electron neutrino background is determined using beam Monte Carlo tuned to the neutrinos

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observed from  $K_{\mu 2}^{\pm}$  decays. This beam prediction is then checked against a direct measurement of the electron neutrino content in the NuTeV data [5]. The predicted and measured electron neutrinos are found to agree: the ratio of measured to Monte Carlo predicted  $\nu_e$  events is  $1.05 \pm 0.03$  in the neutrino beam and  $1.01 \pm 0.04$  in the antineutrino beam [5].

Because of their event topology, electron neutrino interactions all appear as short events in the NuTeV detector. Their contribution (in addition to other corrections which are not shown here) is explicitly included as a modification to the number of short events appearing in the numerator of the predicted experimental ratio:

$$R_{exp}^{MC} = (N_{exp}^{S,MC} + N_{exp}^{\nu_e,MC}) / N_{exp}^{L,MC} \quad (3)$$

in both neutrino and antineutrino modes. Any overestimate of the electron neutrino contribution (for example, that would result from neglecting  $\nu_e \rightarrow \nu_s$  oscillations) would lead to an overestimate of the predicted ratio,  $R_{exp}^{MC}$ , and hence a larger measured value of NuTeV  $\sin^2 \theta_W$ . Importantly, any adjustment to the electron neutrino flux needed to reduce the NuTeV  $\sin^2 \theta_W$  value and bring the result into better agreement with expectation must additionally satisfy the direct constraint from the NuTeV data itself [5]. Here, we consider several such possibilities.

## II. NEUTRINO OSCILLATIONS

To gain an understanding of the potential impact of electron neutrino oscillations in NuTeV, first consider the approximation of a simple two-flavor ( $\nu_e \rightarrow \nu_s$ ) oscillation probability:

$$P = \sin^2 2\theta \sin^2(1.27 \Delta m^2 L/E). \quad (4)$$

The fundamental parameters describing the oscillation are  $\sin^2 2\theta$ , the mixing between the flavors, and  $\Delta m^2$ , the squared mass difference between the neutrinos. The experimental parameters are  $L$ , the baseline, and  $E$ , the incident neutrino energy. In general, oscillations become observable when  $\Delta m^2 L/E \sim 1$  or larger. The high beam energy and short baseline of NuTeV lead to a small value of  $L/E$ , therefore requiring a large value of  $\Delta m^2$  (of a few  $\text{eV}^2$  or greater) to compensate.

In the few  $\text{eV}^2$  range of  $\Delta m^2$ , the Bugey reactor experiment sets the best limit on the mixing angle for  $\bar{\nu}_e$  disappearance [9]. Reference [4] shows that, in a 3+1 model, the NuTeV result implies  $\Delta m^2 \sim 10 \text{ eV}^2$  and  $\sim \sin^2 2\theta = 0.4$ , which would have produced a clear signal in Bugey; therefore, this solution is directly excluded. The situation for 3+2 models, however, could differ. In such a model, the probability for electron neutrino disappearance at high  $\Delta m^2$ , with mixing matrix parameters denoted as  $U$  rather than mixing angles, is given by:

$$P = 4[U_{e4}^2(1 - U_{e4}^2) \sin^2 x_{41} + U_{e5}^2(1 - U_{e5}^2) \sin^2 x_{51} - U_{e4}^2 U_{e5}^2 (\sin^2 x_{41} + \sin^2 x_{51} - \sin^2 x_{54})] \quad (5)$$

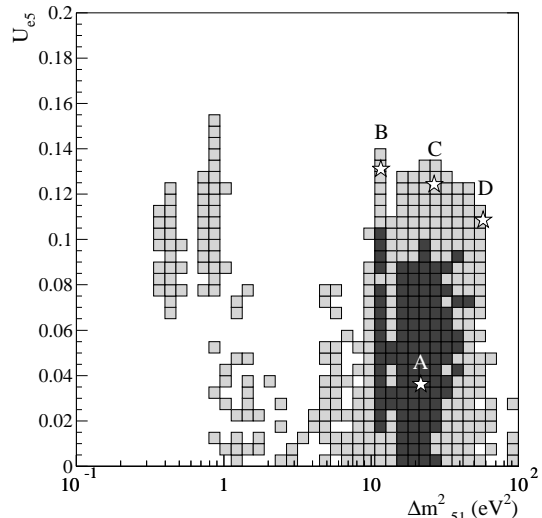


FIG. 1: 90% (dark grey) and 99% (light grey) CL allowed regions in  $(\Delta m_{51}^2, U_{e5})$ -space for CP-conserving (3+2) models. The stars labeled A, B, C, and D indicate the four models evaluated for their impact on the NuTeV  $\sin^2 \theta_W$  analysis.

where  $x_{ij} = 1.27 \cdot \Delta m_{ij}^2 (L/E)$ . Such 3+2 models can fit the world's oscillation data with many different values of mass splittings and mixing parameters [6]. Those which provide a good description of the data tend to have  $\Delta m_{14}^2 \sim 1 \text{ eV}^2$  and  $\Delta m_{51}^2 > 10 \text{ eV}^2$ .

For NuTeV, which has a small  $L/E$ , in the case where  $\Delta m_{41}^2 \ll 10 \text{ eV}^2$ , (which is the 3+2 best fit case), and taking  $x_{41} = 0$  and  $x_{54} = x_{51}$ , the oscillation probability simplifies to:

$$P = 4U_{e5}^2(1 - U_{e5}^2) \sin^2 x_{51}, \quad (6)$$

analogous to Equation 4. Figure 1 shows the 90% and 99% CL allowed regions in the  $\Delta m_{51}^2$  and  $U_{e5}$  mixing space, as determined using the methods described in Reference [6]. The short-baseline data yielding the parameter space relevant for this study include Bugey [9], CCFR84 [10], CDHS [11], CHOOZ [12], KARMEN2 [13], LSND [14], and NOMAD [15].

## III. IMPACT OF 3+2 MODELS ON THE NUTEV ELECTROWEAK RESULTS

Given the increase in possible parameter space inherent in 3+2 models, we ask whether there is an oscillated  $\nu_e$  flux which can account for the NuTeV electroweak results. To answer this question and demonstrate the impact of a 3+2 model neutrino oscillations on the NuTeV data, four representative points are selected within the allowed region as indicated in Figure 1. These points are the best fit model (A), a high mixing model with lower mass (B), a high mixing model with higher mass (C), and a high mass model (D). The best fit point (A)

no oscillation	NuTeV measurement	expectation	deviation
$R_{exp}^\nu$	$0.3916 \pm 0.0013$	0.3950	$-2.6\sigma$
$R_{exp}^{\bar{\nu}}$	$0.4050 \pm 0.0028$	0.4066	$-0.6\sigma$
$\sin^2 \theta_W$	$0.2277 \pm 0.0016$	0.2227	$+3.0\sigma$
model B	NuTeV measurement	expectation	deviation
$R_{exp}^\nu$	$0.3916 \pm 0.0013$	0.3949	$-2.5\sigma$
$R_{exp}^{\bar{\nu}}$	$0.4050 \pm 0.0028$	0.4065	$-0.5\sigma$
$\sin^2 \theta_W$	$0.2277 \pm 0.0016$	0.2227	$+3.0\sigma$
model C	NuTeV measurement	expectation	deviation
$R_{exp}^\nu$	$0.3916 \pm 0.0013$	0.3948	$-2.5\sigma$
$R_{exp}^{\bar{\nu}}$	$0.4050 \pm 0.0028$	0.4062	$-0.4\sigma$
$\sin^2 \theta_W$	$0.2275 \pm 0.0016$	0.2227	$+2.9\sigma$
model D	NuTeV measurement	expectation	deviation
$R_{exp}^\nu$	$0.3916 \pm 0.0013$	0.3945	$-2.2\sigma$
$R_{exp}^{\bar{\nu}}$	$0.4050 \pm 0.0028$	0.4059	$-0.3\sigma$
$\sin^2 \theta_W$	$0.2271 \pm 0.0016$	0.2227	$+2.7\sigma$

TABLE I: Comparison of NuTeV electroweak results assuming no  $\nu_e$  oscillations (default) to the results assuming three CP-conserving 3+2 oscillation models (B,C,D in Fig. 1). In all cases, the same event selection criteria as in [1] is applied.

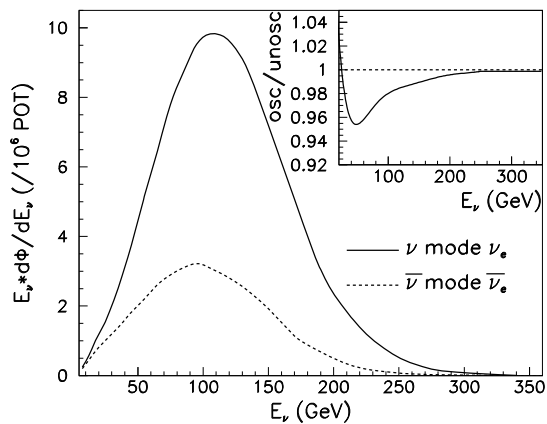


FIG. 2: Unoscillated NuTeV  $\nu_e$  flux prediction in each mode. Inlay shows the ratio of the predicted oscillated/unoscillated  $\nu_e$  fluxes as a function of energy for Model D. The change is within the errors of the NuTeV  $\nu_e$  measurement [5].

was eventually omitted from the study because it represented such a small correction to the unoscillated flux

(as expected from Equation 6) that it had a negligible impact on NuTeV  $\sin^2 \theta_W$ .

For each set of possible parameters, a  $\nu_e$  survival probability is calculated as a function of energy. This probability is then used to correct the estimated NuTeV  $\nu_e$  and  $\bar{\nu}_e$  fluxes. The resulting difference is very small in all cases, being largest for the high mass Model D (Figure 2). The total integrated  $\nu_e$  flux prediction changes by 0.2% (Model B), 0.8% (Model C), and 1.8% (Model D), hence satisfying the NuTeV  $\nu_e$  data constraint [5]. Based on each of the “oscillated”  $\nu_e$  and  $\bar{\nu}_e$  fluxes, the  $R_{exp}^{MC}$  predictions are then recalculated in both neutrino and antineutrino modes, and a new value of  $\sin^2 \theta_W$  is extracted. In Table I, we report the deviation of the measured  $R_{exp}^{\nu,\bar{\nu}}$  and  $\sin^2 \theta_W$  values for the three models: B, C, and D. The magnitude and sign of the shift indicates the expectation if the NuTeV data had been analyzed using the oscillated electron neutrino fluxes. All of the adjusted fluxes move the NuTeV results into better agreement with the standard model, by construction. Model D provides the largest impact: shifting  $R_{exp}^\nu$  and  $R_{exp}^{\bar{\nu}}$  into better agreement with expectation by  $0.4\sigma$  and  $0.3\sigma$ , respectively. Model D reduces the NuTeV  $\sin^2 \theta_W$  discrepancy with the standard model from  $3.0\sigma$  to  $2.7\sigma$ .

We have studied three points representative of extreme masses and mixings within the allowed region of 3+2 models, and conclude that  $\nu_e \rightarrow \nu_s$  oscillations in this model do not yield a significant impact on NuTeV’s electroweak results. The largest shift in  $\sin^2 \theta_W$  is created by a high mass model (e.g. model D), but even such a high mass model would only affect the NuTeV value of  $\sin^2 \theta_W$  by roughly  $0.3\sigma$ . Therefore, a 3+2 model with  $\nu_e \rightarrow \nu_s$  oscillations cannot explain the NuTeV electroweak results by itself.

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